S&C FY02 ANNUAL REVIEW MEETING

Integrated Intelligent Industrial Process Sensing and Control Applied to and Demonstrated on Cupola Furnaces

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Presented by

D. E. Clark, INEEL

Project Description

- *Collaborative effort that aims at the development of generic technology for improving operation of industrial processes through the integration of process sensing and control.*

- *This is achieved through the following*

  - *Development of a generic object oriented architecture for integration of various system components*

  - *Development of algorithms for Multi Modal Sensor Fusion, or MMSF*

  - *Integration of MMSF and intelligent control*

  - *Application of developed technology to cupola furnaces*

Collaborations

Technical Development

Tennessee Tech

M. Abdelrahman
J. Frolik
M. Haggard
W. Mahmoud

INEEL

D. E. Clark
E. D. Larsen

Utah State

K. L. Moore

Industrial Oversight

AFS

J. A. Santner

Advisory Board

Mark Bauer, GM
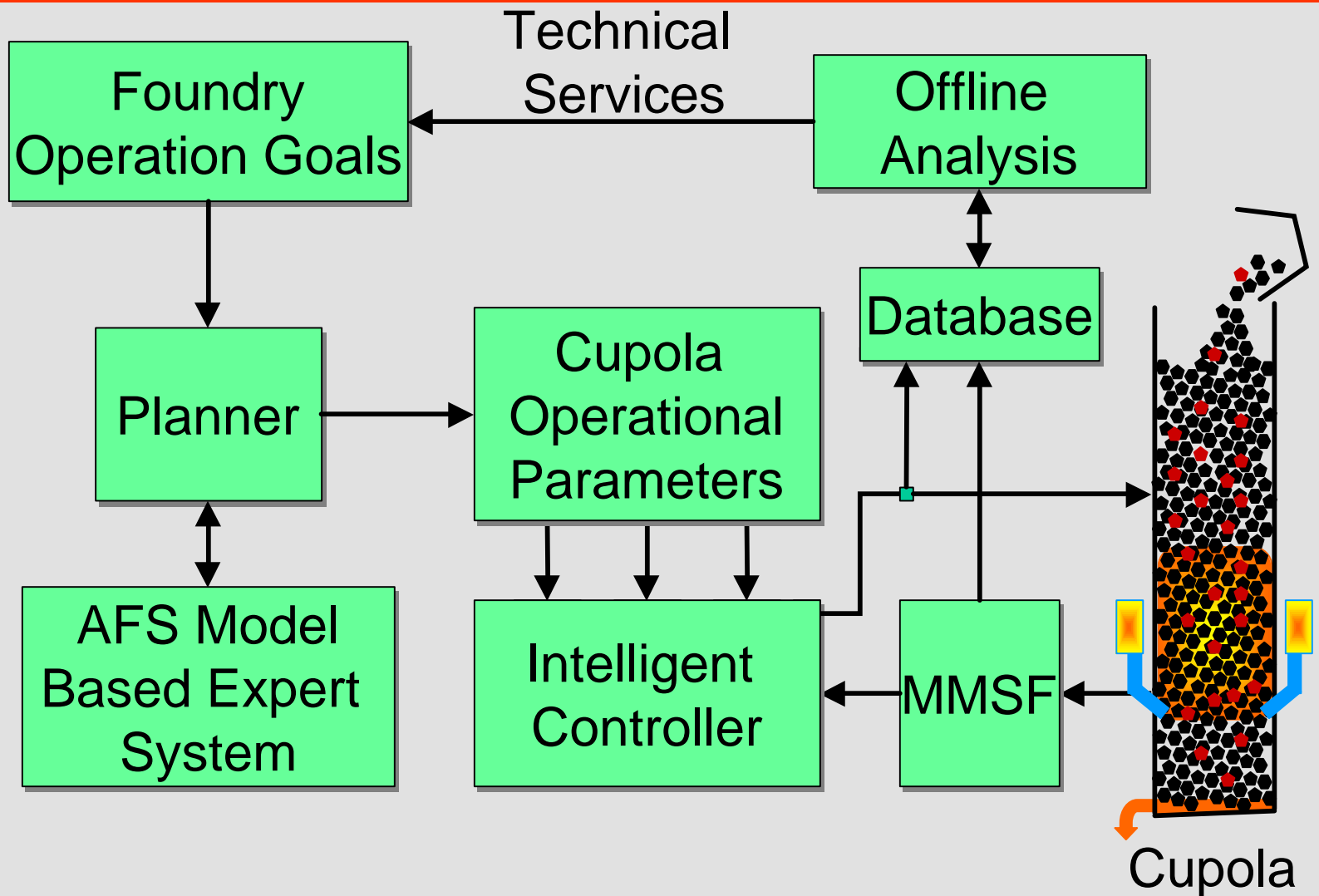Mike Barstow, US Pipe
Sy Katz, Katz Associates

Demonstration

**DOE
Albany Research Center**

P. L. King

Overall System Vision

Technical Services

Foundry Operation Goals → Planner → Cupola Operational Parameters

Offline Analysis → Foundry Operation Goals

Offline Analysis ↔ Database

Planner ↔ AFS Model Based Expert System

Cupola Operational Parameters → Intelligent Controller

Intelligent Controller ← MMSF

Cupola

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Project Objectives/Goal

- **IOF need(s) addressed by this technology**
  - Improved sensing and control technology is an issue of importance to most IOF industries.
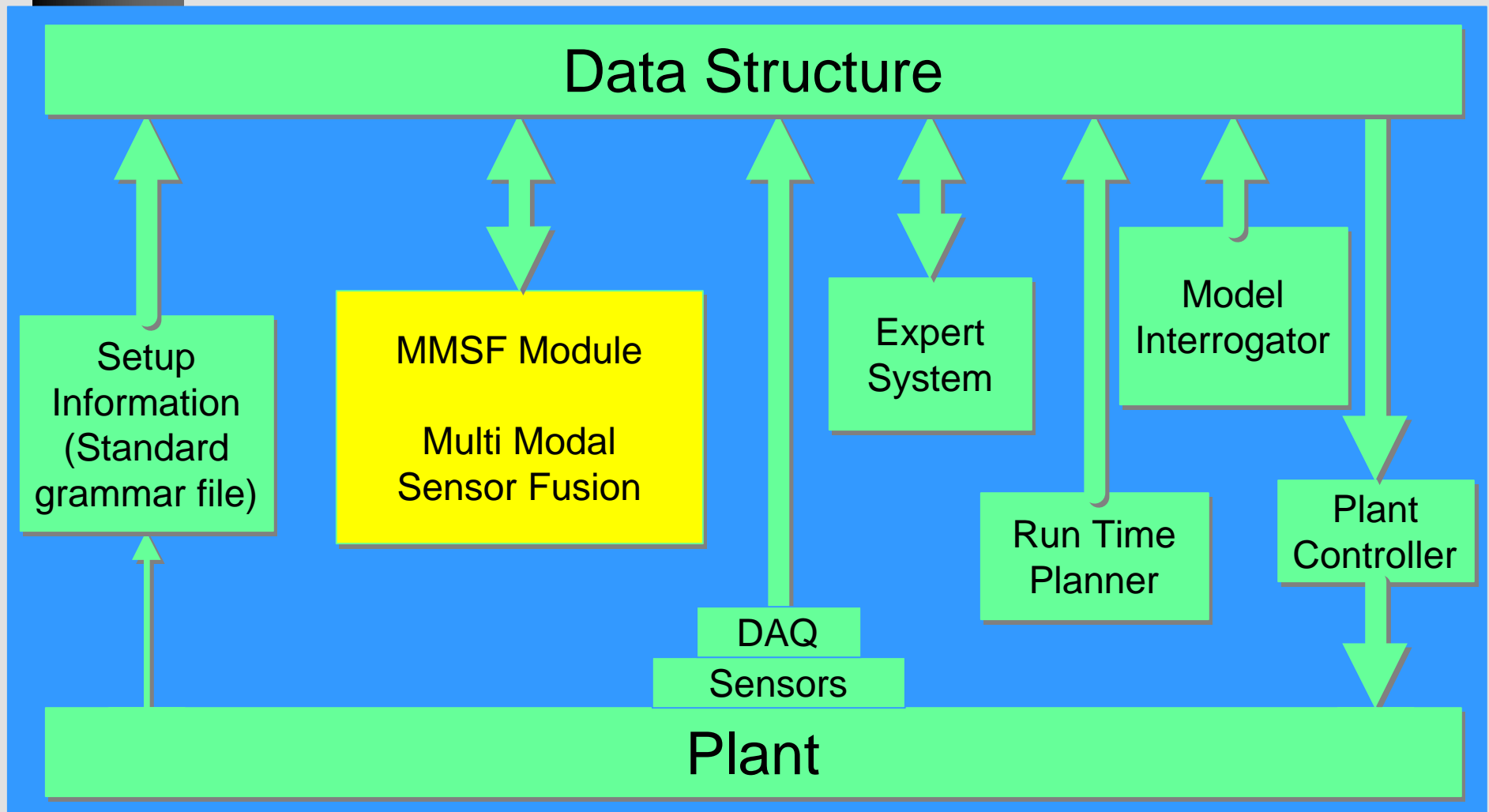 - Direct Application to : Metal Casting
- **Objectives**
  - Develop Generic Technology for Improved Process Sensing
  - Technology for Integration of Sensing and Control
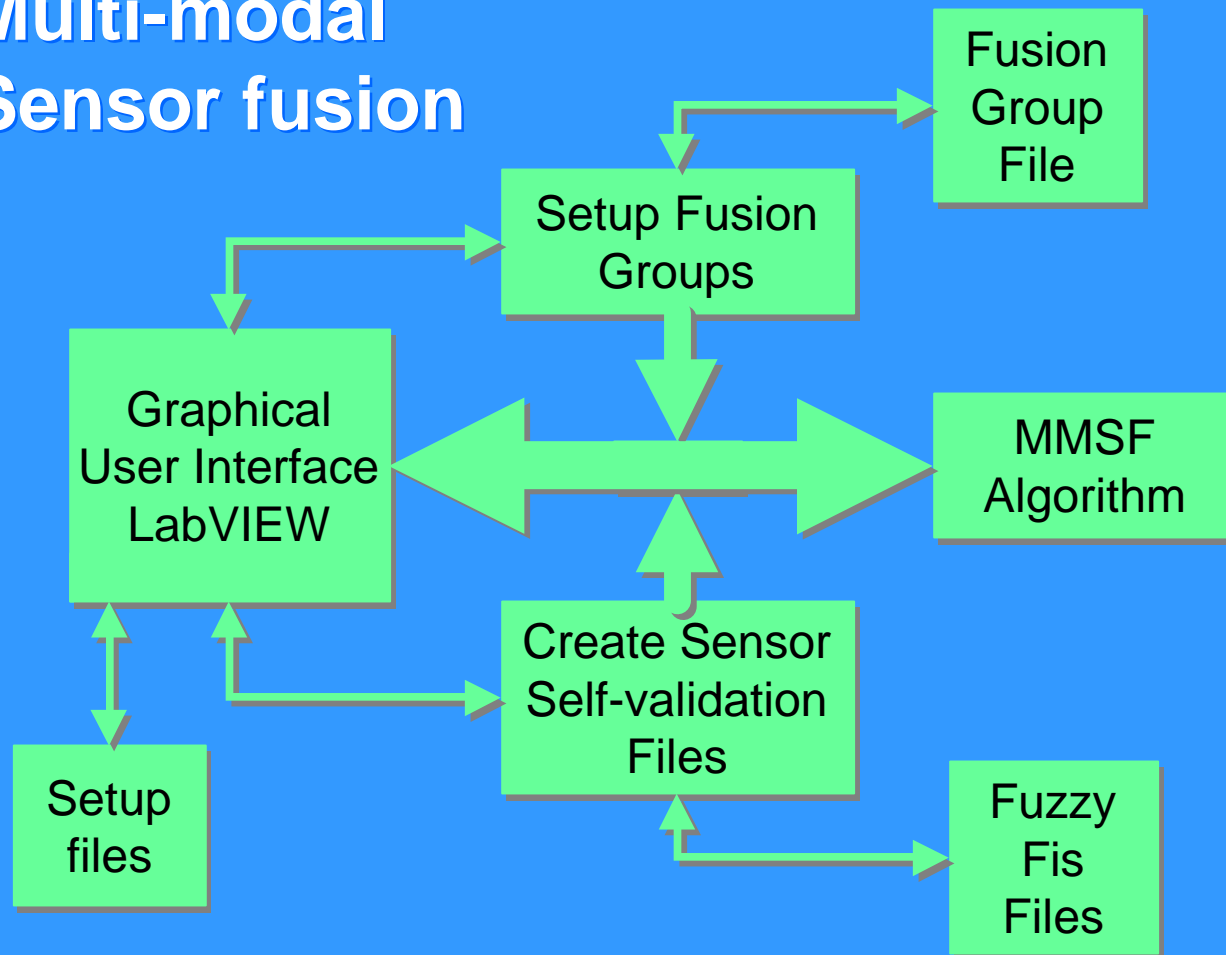 - Demonstration of Technology on Cupola Furnaces
- **Overall goal**
  - Improved process monitoring and control by utilizing all available multi-modal sources of information.

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System Architecture

Data Structure

Setup Information (Standard grammar file)

MMSF Module

Multi Modal Sensor Fusion

Expert System

Model Interrogator

Run Time Planner

Plant Controller

DAQ Sensors

Plant

MMSF Module Architecture

Multi-modal Sensor fusion

- Fusion Group File
- Setup Fusion Groups
- Graphical User Interface LabVIEW
- MMSF Algorithm
- Setup files
- Create Sensor Self-validation Files
- Fuzzy Fis Files

Technical Risks/Innovation

- **Technical risks**
  - Cupola furnace sensing and control practices have remained generally untouched for a long time
  - Sensors for measuring cupola furnace parameters such as melt-rate are not well developed
- **Innovation**
  - New Algorithms for sensor fusion (Basic Research)
  - New Algorithms for integration of intelligent control and sensor fusion based on confidence in measurements
  - Generic architecture that allows for easy integration of new components and adaptation of the developed system to new industrial applications
- **Advancement of state-of-the-art over competition**
  - Control has been limited to control of input parameters such as blast rate
  - Control of process variables such as iron composition is more desirable, and is the goal of the current project

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Task Performance

Past Technical Milestones

| Milestone	Due Date	Completion Date	Comments
Sensor Fusion	First Year	On Time	
Intelligent Control	Third Year	On Time	
Generic Architecture	Second Year	On Time	Improvements continue
Hardware Implementation			Proof of concept
Implementation on Albany Cupola	Third Year	Delay of 6 Months	Delayed due to recent tragic events
Demonstration Plans	Third Year	Delay of 9 Months	Still Going due to recent tragic events

Progress Toward Performance Goals

- Innovative sensor fusion algorithms based on a new concept has been developed, implemented and tested.
  - Allow for the fusion of quasi-redundant sensors data
  - Produce a best estimate and a parameter indicating the degree of confidence in the measurement
- The preliminary algorithms were presented in 4 refereed articles
  - American Control Conference (ACC) proceedings
  - *IEEE Transactions on Instrumentation and Measurements*.
- Complete Algorithms under preparation for publication and patenting

Multiple Sensor Fusion

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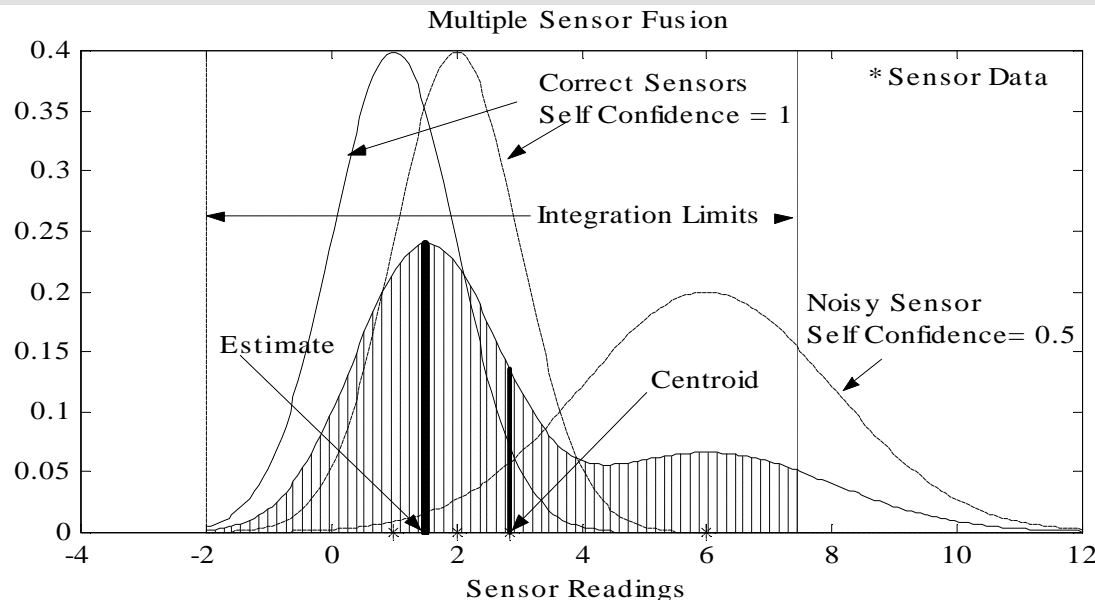
Progress Toward Performance Goals

- An algorithm for Integration of Sensor Fusion and Intelligent Control developed, implemented and tested
- Results presented:
  - Refereed conference paper in the ACC 2002
  - Will appear in 2002 in *Transactions of Instrumentation Society of America*

WA - Weighted Avg.
K_h and K_l - Controller Defined Before
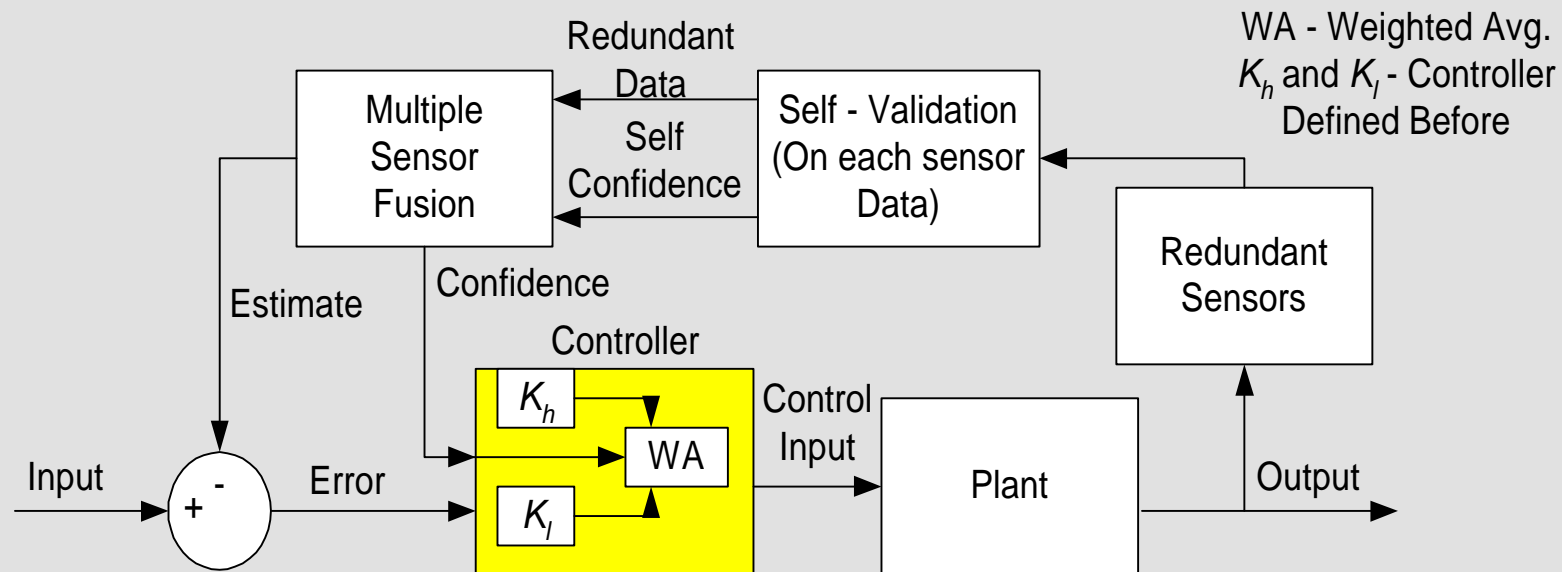
Speed of response depends on confidence
In measurements

Progress Toward Performance Goals

– An adaptation of the generic algorithms for the cupola furnace was developed, implemented and tested.

– A fuzzy logic-based controller that controls %C, %Si, melt rate, and temperature by adjusting coke-to-metal ratio, charge composition, blast rate, and Oxygen

– Results presented at the AFS congress in 2002 and will appear in the *Transactions*

Progress Toward Performance Goals

- A Generic package was developed in LabVIEW
  - A leading instrumentation software package
  - Integrates the developed system components into a working system that can be easily modified
  - Can be considered a Beta version for a commercial implementation of the developed algorithms
- Current Modules include:
  - Plant Interface
  - Monitoring System
  - Sensor Fusion Module
  - Virtual Sensors Module
  - Controller Module
  - Planner Module

Progress Toward Performance Goals

- FPGA (Floating Point Gate Array) implementations of a subset of developed sensor fusion algorithms have been developed, implemented and tested

- Developed system interfaced with the cupola furnace at the DOE Albany Research Center, Oregon, and successfully tested

- Several demonstration runs have been performed and data collected

  - Results illustrate system's flexibility and potential to improve cupola furnace operation.

- **In Summary, the project has achieved all the technical objectives. The remaining demonstration plans will be used to further illustrate the capabilities of the developed system.**

Publications Supported by Project

Refereed Journal Publications

1. "A methodology for self-validation, fusion and reconstruction of quasi-redundant sensors," *IEEE Transaction on Instrumentation and Measurement.* , Vol. 50, No. 6, December 2001.
2. "Integration Of Multiple Sensor Fusion In Controller Design," Accepted for Publication in the *Transactions of Instrumentation Society of America, 2002.*
3. "Fuzzy Control Of A Cupola Iron Melting Furnace," To Appear in *Transactions of American Foundry Society, 2003.*

Refereed Conferences

4. "INTEGRATION OF MULTIPLE SENSOR FUSION IN CONTROLLER DESIGN," in proceedings of the the American Control Conference, Anchorage, AK, May 2002.

- "Fuzzy Control Of A Cupola Iron Melting Furnace," AFS Congress, Kansas City, MO, May 2002.
- "Wavelet-Based Sensor Fusion for Data with Different Sampling Rates," *," in Proceedings of American Control Conference,* Washington D.C., June 2001.
- "A Methodology For Fusion Of Redundant Sensors*," in Proceedings of American Control Conference,* Chicago, IL, June 2000.
- "Synthesis of quasi-redundant sensor data: a probabilistic approach," *," in Proceedings of American Control Conference,* Chicago, IL, June 2000.
- "Fuzzy rules for automated sensor self-validation and confidence measure*," in Proceedings of American Control Conference,* Chicago, IL, June 2000.
- "A convenient methodology for the hardware implementation of fusion of quasi-redundant sensors," *Proceedings of 32nd SSST Conference,* Tallahassee, FL, Mar 2000, pp. 349-353.
- "A Methodology for Integrating Multiple Sensor Fusion in the Controller Design," in *Proceedings Of 32nd SSST conference*, Tallahassee, FL, March 2000, pp. 115 -118.
- "Intelligent Control of Cupola Furnaces," in Proceedings of the 34th SSST conference, Huntsville, AL, March 2002, pp. 435-440.

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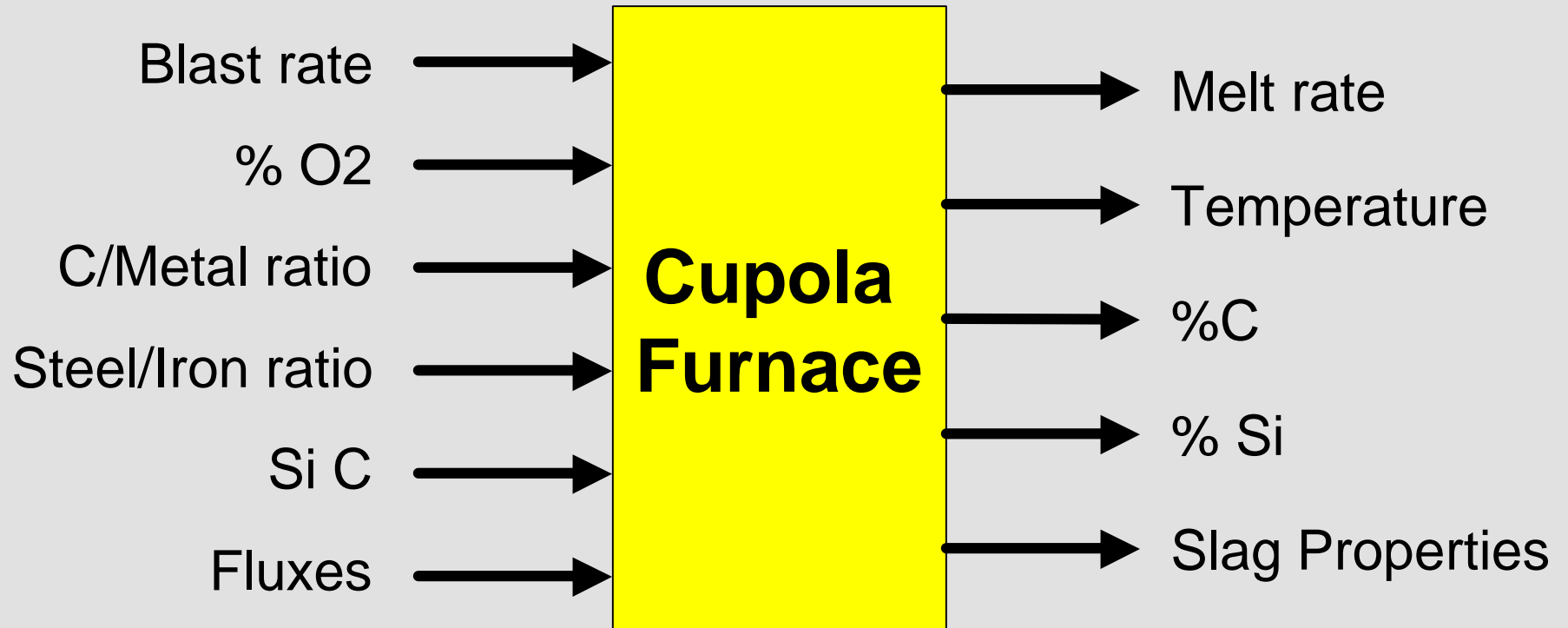# MS Theses Supported by Project

- **Tennessee Technological University**
  - *Confidence-based Integration Of Multiple Sensor Fusion Into Controller Design*, Param. Kanadasamy, 2000
  - *Wavelet Based Sensor Fusion For Multiple Sampling Rate Data*, Min Luo, 2001
  - *A Methodology for Multi-Modal Sensor Fusion*, Vipin Vijayakumar, 2001
  - *Hardware/Software Codesign – Efficient Algorithms for Hardware Synthesis from C to VHDL*, S. Sankaran 2001
  - *Comparison of Cordic Algorithms Implementation on FPGA Families*, Srikala Vadlamani 2002
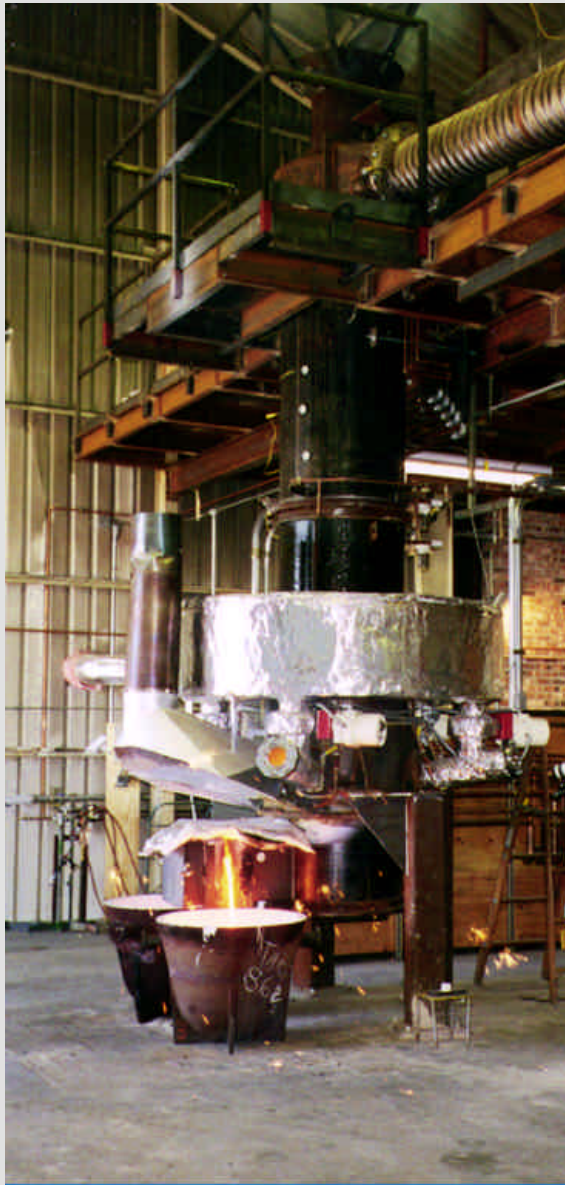 - (Work in Progress) Jie Chen, 12/2002

- **Utah State University**
  - Multi-dimensional Data Structure for Cupola Information Processing, Avinash Seegehalli, 2000
  - (Work in Progress) Spencer Anderson, 2002

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Demonstration On Cupola Furnace

Blast rate →

% O2 →

C/Metal ratio →

Steel/Iron ratio →

Si C →

Fluxes →

Cupola Furnace

→ Melt rate

→ Temperature

→ %C

→ % Si

→ Slag Properties

Input/Output Cupola Control Parameters

Demonstration

Experimental Cupola,
DOE Albany Research Center,
Oregon

18-inch diameter

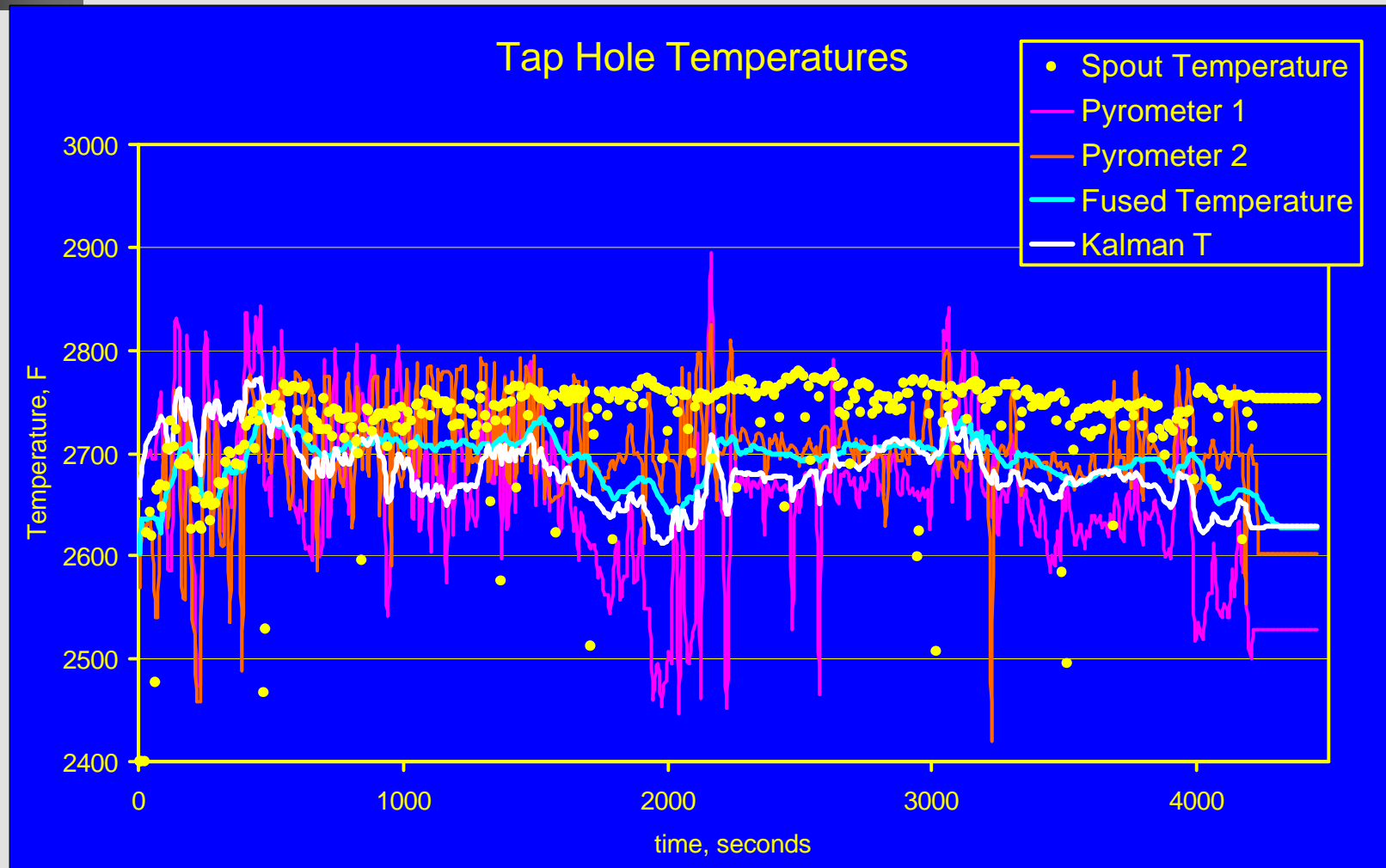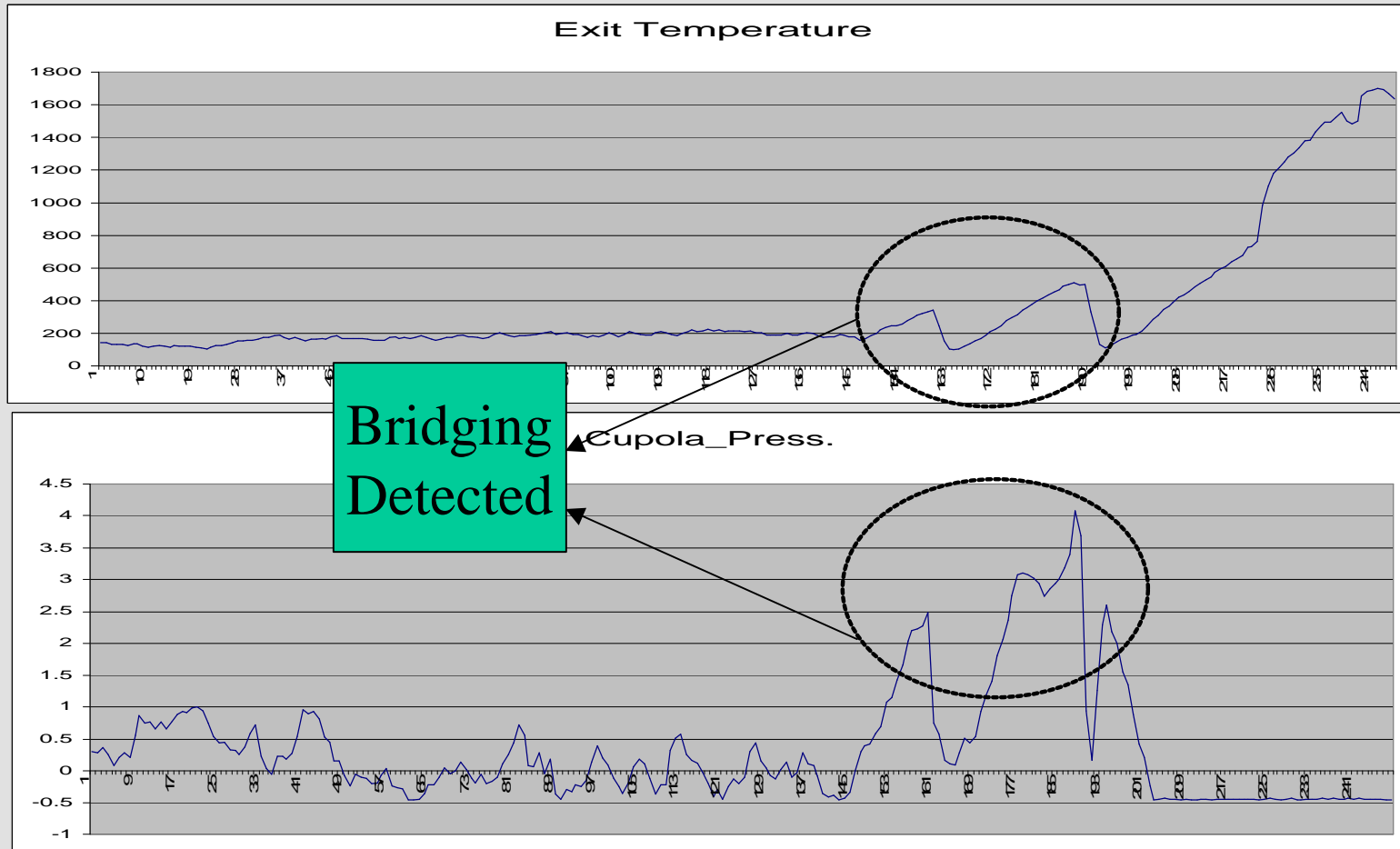Fully instrumented

Analytical capabilities

Demonstration Results

Tap Hole Temperatures

Legend:
- Spout Temperature
- Pyrometer 1
- Pyrometer 2
- Fused Temperature
- Kalman T

y-axis: Temperature, F (2400, 2500, 2600, 2700, 2800, 2900, 3000)

x-axis: time, seconds (0, 1000, 2000, 3000, 4000)

Monitoring of Tap hole from Albany Cupola Furnace

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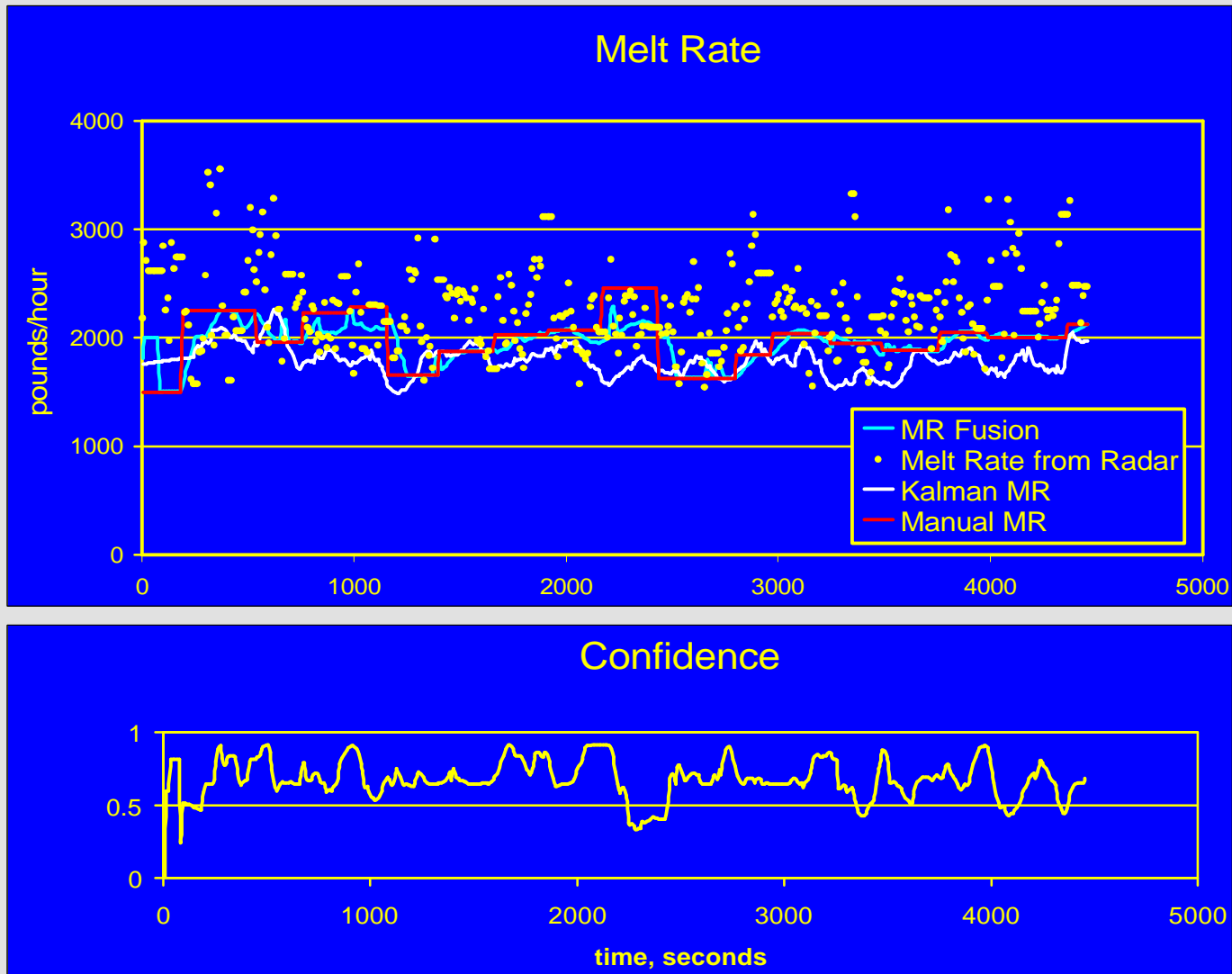# Demonstration Results
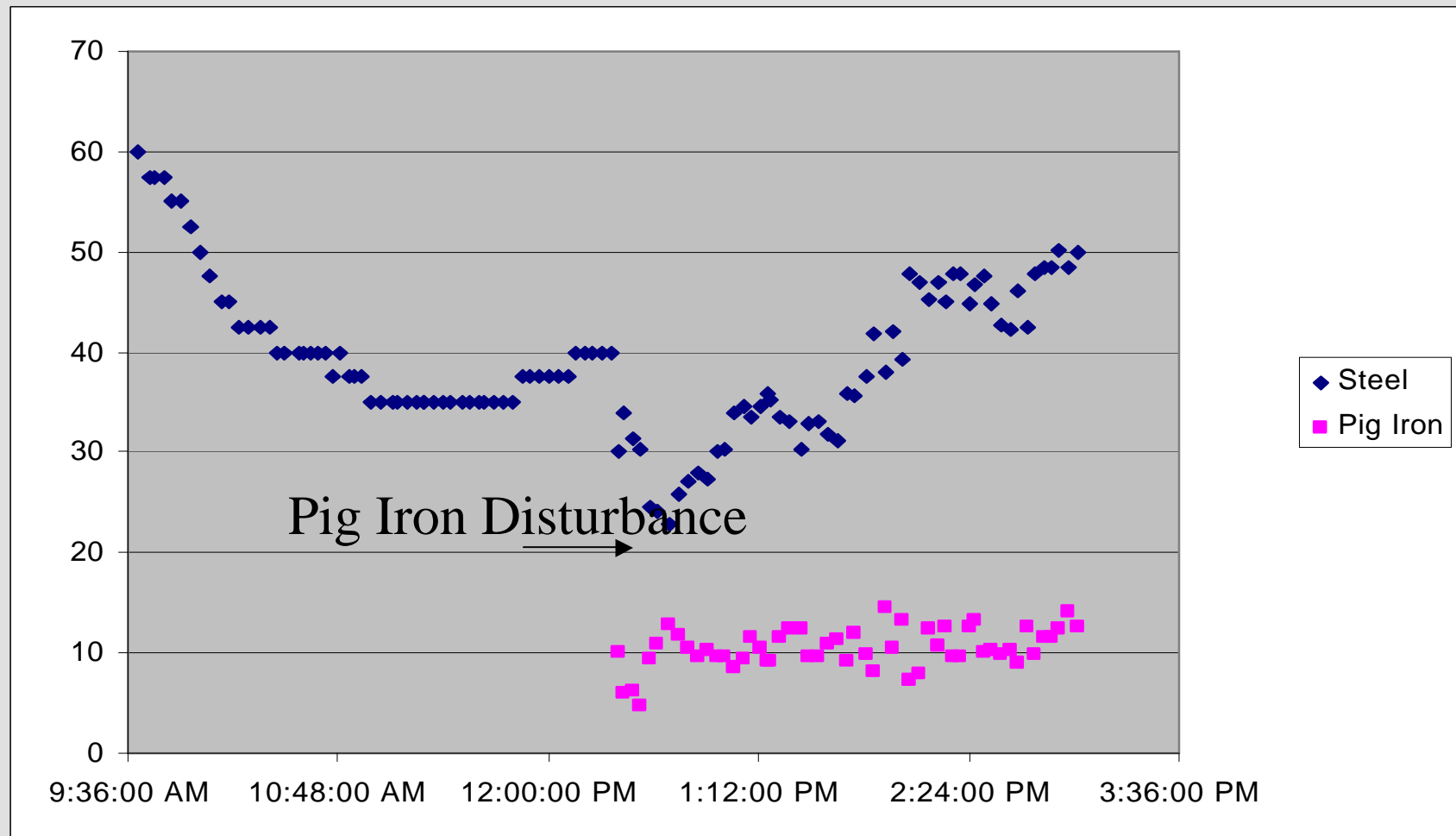
Exit Temperature

Bridging Detected

Cupola_Press.

Monitoring System detects Bridging by Monitoring Exit Temperature and Cupola Pressure

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Confidence in MR Estimate

Melt Rate

Confidence

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Automatic Control of Steel/Cast Iron

Control of Carbon

%C

Expected new level if
Disturbance is not rejected

Start Control

Disturbance in Composition
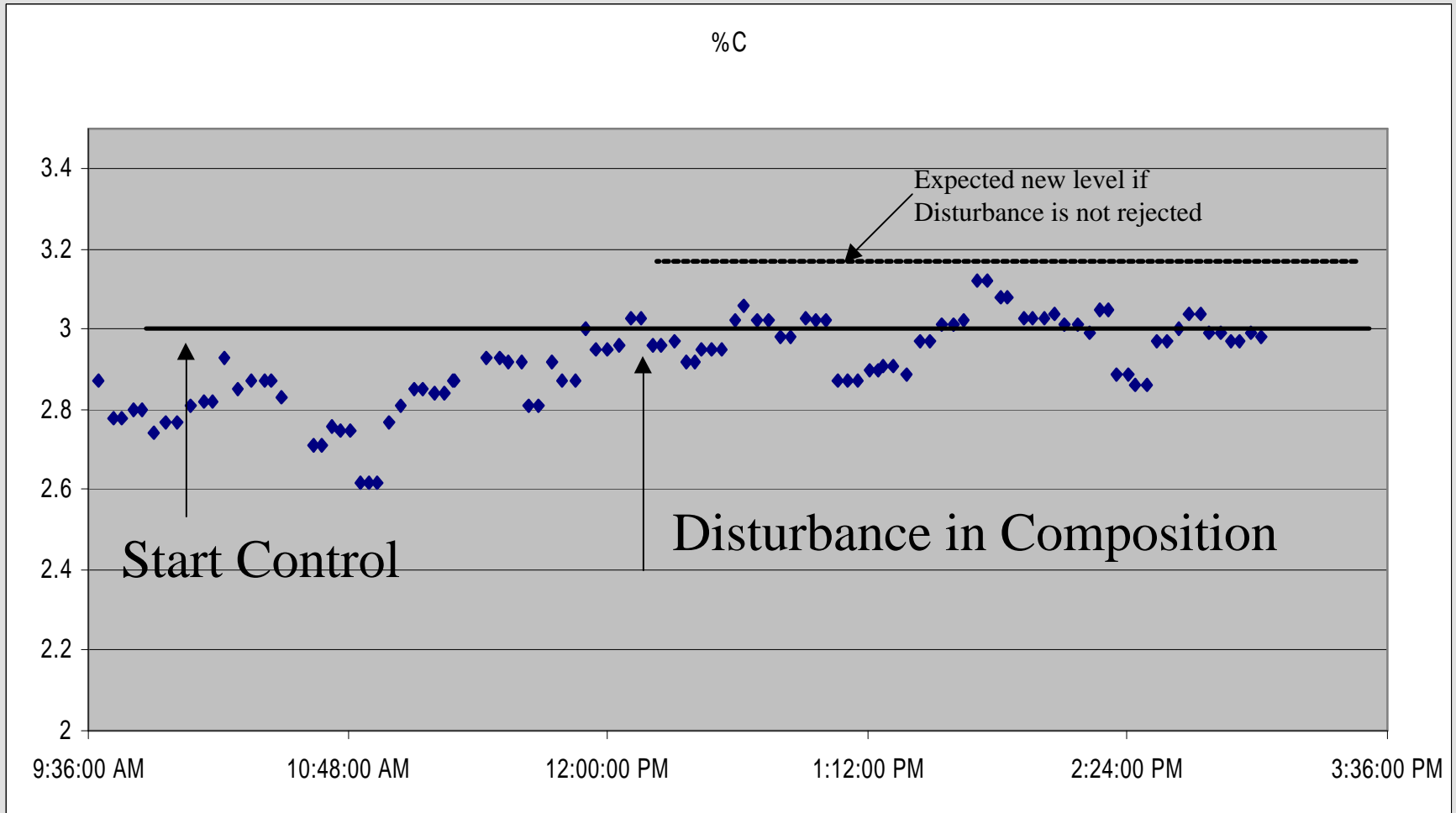
Commercialization

- **Proposed plant tests/deployments, and planned use in IOF manufacturing plant(s)**
  - As set forth in the proposal, the technology is being demonstrated on a research cupola facility in Albany Oregon
- **Commercialization path & partners**
  - The generic part of the results of the research are published in refereed journals and presented at AFS congress
  - Several presentations to AFS cupola committee regarding research results have been made to seek industrial partners
  - The project has industrial advisory boards from manufacturing facilities such as US Pipe and GM that are interested in improving cupola melting technology
  - *Funding for implementation of the developed technology in a foundry is currently sought from DOE programs with such focus.*

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Performance Merits

- **Improving energy efficiency**
  - How will energy be saved?
    - Better control over cupola parameters such as %C and metal temperature would produce less return scrap
    - Monitoring and detection of operational problems such as bridging early can reduce the impact of such problems over the quality of molten metal

  - What are the energy savings
    (per installed unit and nationwide)?
    - A 10% improvement in the efficiency of cupola operation would result in savings of the order of 0.010 Quads/Year

Performance Merits

- **Improving product quality**
  - How will product quality be improved?
    - Metal casting products are affected by variations in the chemical composition of the molten iron as well as the iron temperature.
    - The developed technology would give better control over these parameters and hence a more consistent produce would be expected
  - How will this improvement be quantified?
    - This could be judged by the percentage reduction in the amount of returns

Path Forward

Future Technical Milestones

Milestone	Due Date	Completion Date	Comments
Finish Demonstration Plans	Sep 30,2001	July 31,2002	
Final Report	June 30, 2002	Sep.30,2002	Extension Requested